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Introduction to the China-ADS project and accelerator design

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Introduction to the C-ADS project

Nuclear Power in China

Operating reactors：	10.23 GW_e/13 sets
Constructing reactors：	25.90 GW_e/23 sets
Prepare to construct：	44.27 GW_e/39 sets
Propose to construct:	120.0 GW_e/120 sets

2020

70GWe （5% total electricity）

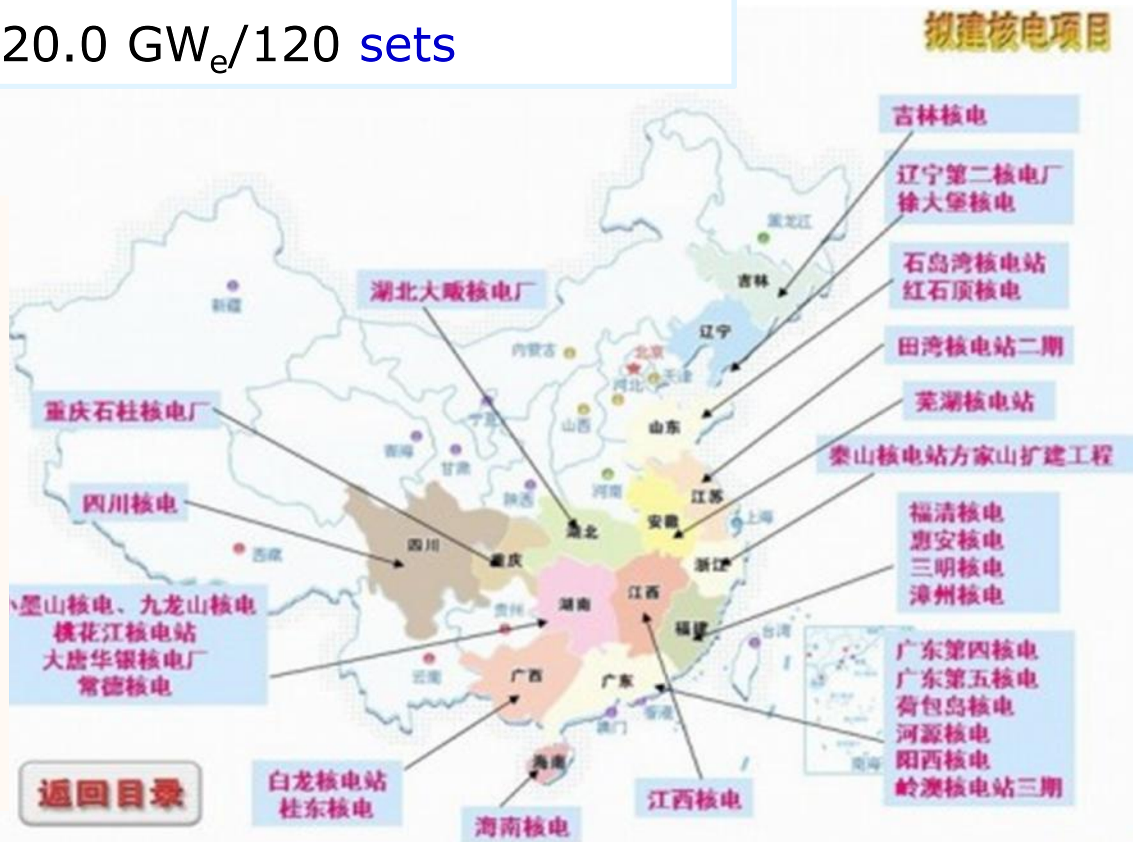
2030

200GWe（10% total electricity）

2050

400GWe（22% total electricity）

May be more than total nuclear power in the world right now！



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Nuclear waste accumulated by 2050 in China

Year	2000	2010	2020	2050
Power (GW)	6	20	40	240
Spend fuel (t)			7200	>50000
Minor actinides (t)			4	>30
Long live fission products (t)			17	>120

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Advanced Nuclear Energy Programs in China

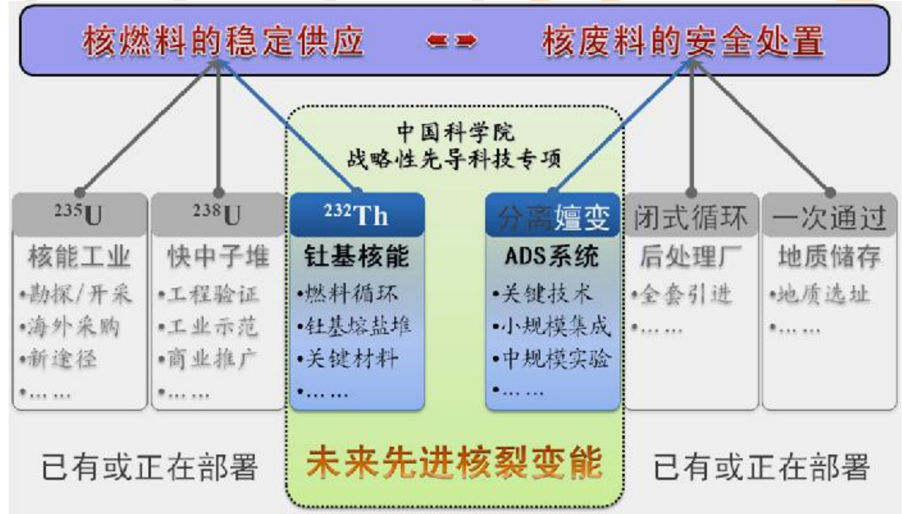
- The strategy of sustainable fission energy in China consoled by top Chinese scientists:
  - Gen-IV reactors for nuclear fuel breeding
  - ADS for transmutation
    - Nuclear waste is a bottleneck for nuclear power development.
    - ADS has been recognized as a good option for nuclear waste transmutation.
- As a long-term program, ADS and TMSR (Thorium-based Melten Salt Reactor) R&Ds will be supported by CAS.
- Budgets for C-ADS and TMSR (both Phase 1) have been allocated by the central government.

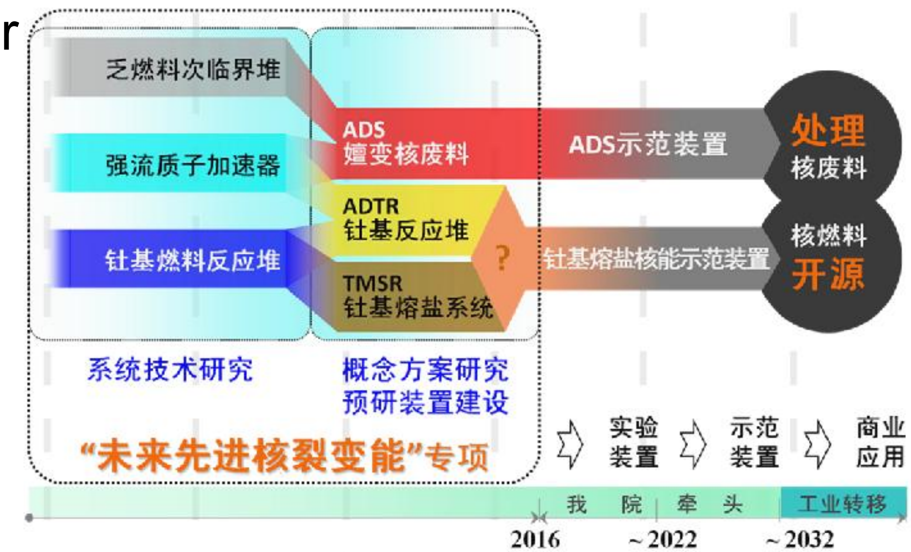
Special Nuclear Energy Program in CAS

- **TMSR**
  - Diversify nuclear fuel source
  (Thorium is richer than uranium and more dispersed on the earth, less waste etc.)

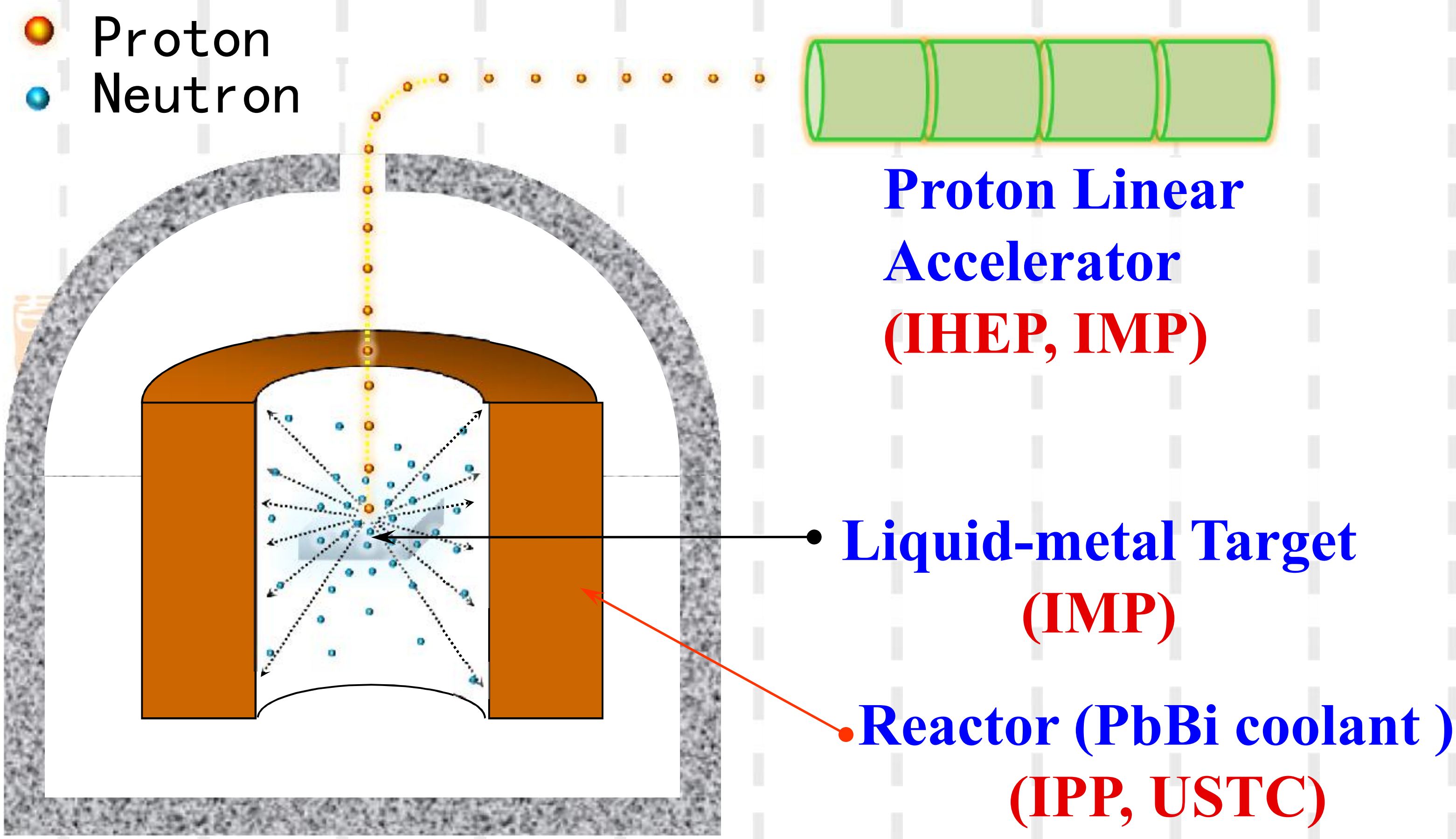
- **ADS**
  - Transmutation of long-lived nuclear waste

- ~2032,
  - Demo facilities for industrial applications





Schematic of C-ADS



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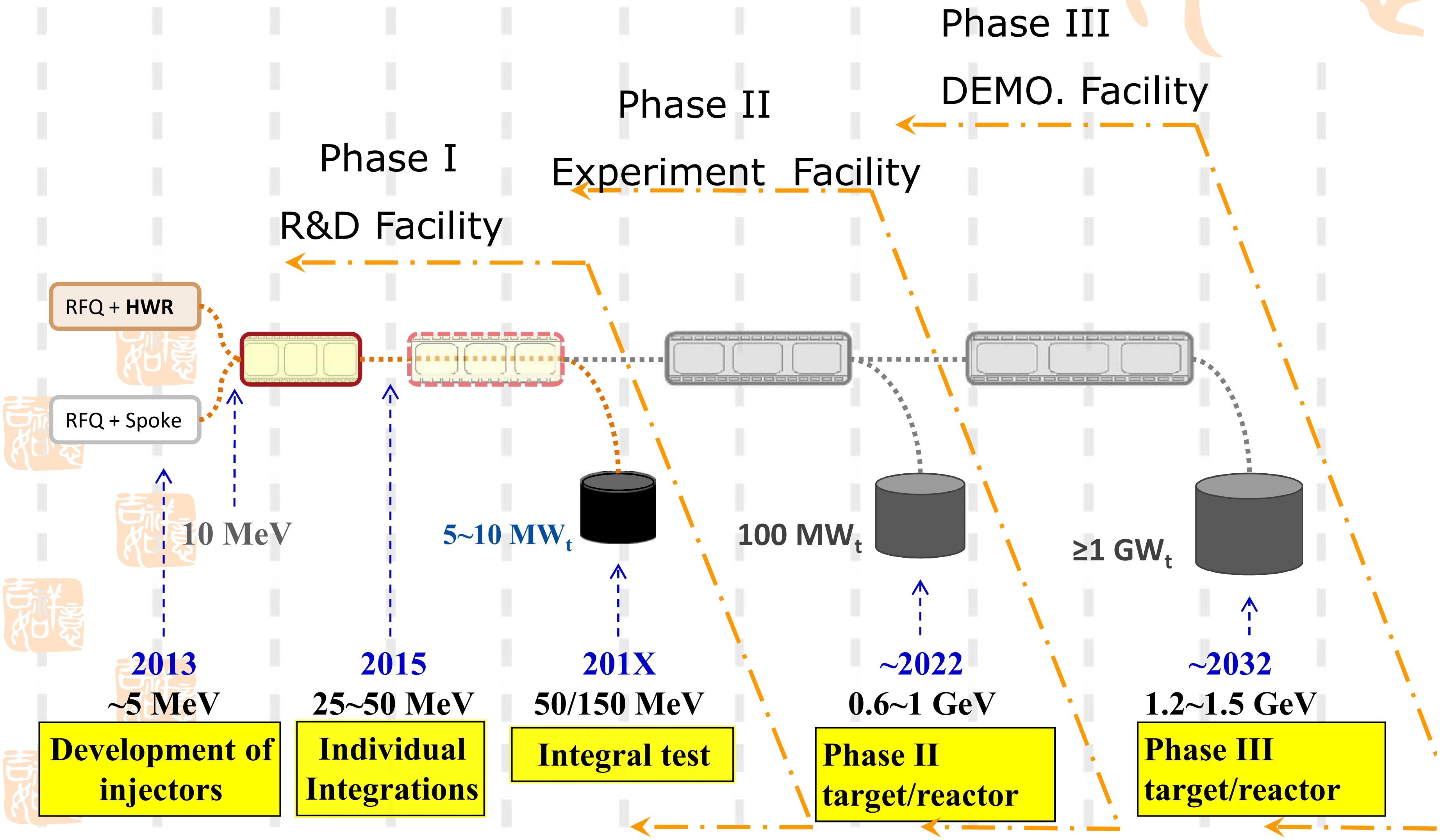
Roadmap of C-ADS program



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R&D Team & Sites for C-ADS

- Team
  - CAS: IHEP, IMP, IPP, USTC, …
  - 3 NP Com. + Univ.
  - Local government cooperation
  - International collaboration
- Host of the future facility
  - A new CAS institute will be established to host the C-ADS facility
  - Site candidate: Erdos (Inner Mongolia)
- R&D infrastructure
  - Labs and infrastructure at the home institutes before the new institute is ready

Organization of C-ADS Phases 0&I

- Three major systems
  - Accelerator:

    IHEP as leader, responsible for one injector and the main linac and

    IMP as collaborator, responsible for another injector

    Joint IHEP-IMP group on accelerator physics
  - Target: IMP as leader
  - Reactor: IPP (Institute of Plasma Physics, as leader) and USTC (University of Science and Technology of China)

- Infrastructure (to be built in leading institutes)
  - Superconducting RF test platform
  - Radio-chemistry study platform
  - Pb-Bi core simulation and mock-up platform
  - Nuclear database
  - Integrated test and general technical support platform

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Preliminary design of the C-ADS accelerator

Main specifications of the C-ADS driver linac

Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
Frequency	162.5/325/650	MHz
Duty factor	100	%
Beam loss	<1 (or 0.3)	W/m
Beam trips /year	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

Design philosophy

- Accelerator choice: superconducting linac is preferred.
  - Straight trajectory: easy extraction and injection.
  - Easy upgrading.
  - Large aperture.
  - Low AC power consumption.
  - Independently powered structures.
- To meet the very strict reliability requirement
  - De-rating of critical components (over-design).
  - Component redundancy and spares on line.
  - Component failure tolerance.

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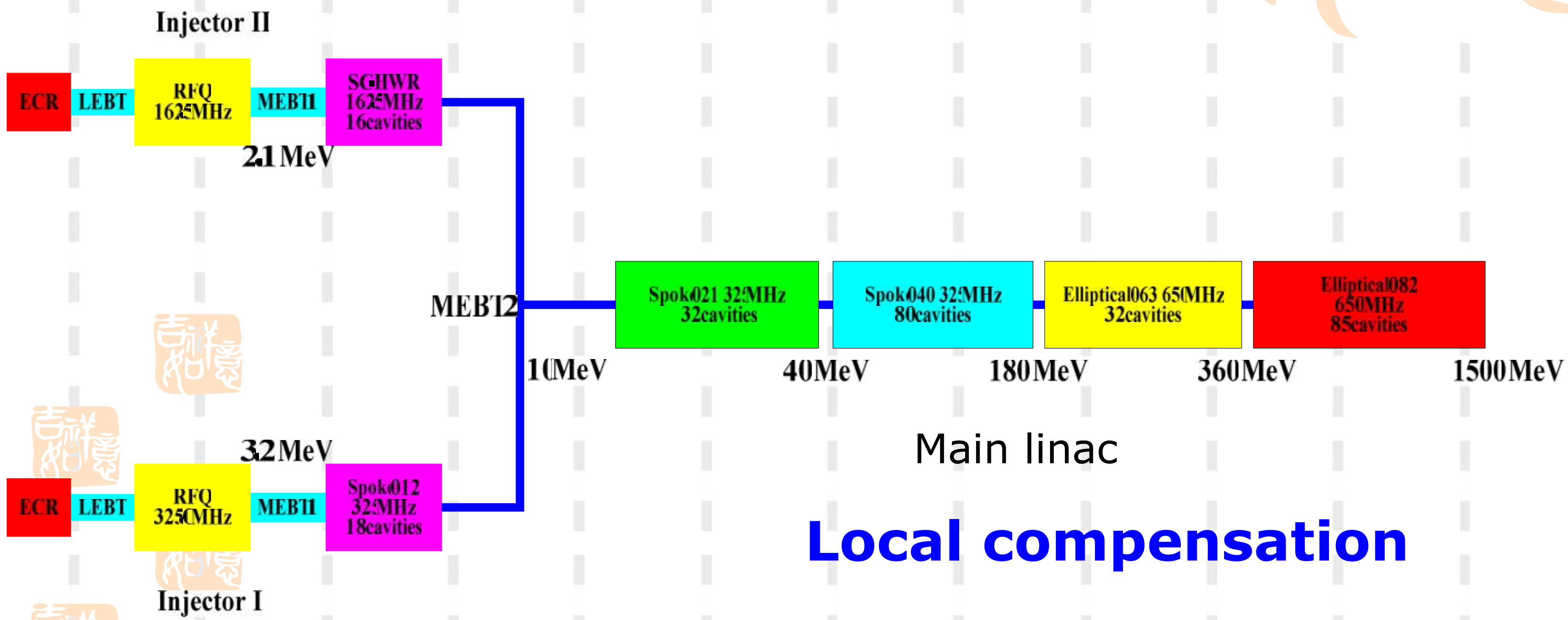
Layout of the C-ADS linac



Local compensation

'Hot stand-by'

Two identical injectors on line, either with scheme injector-1 or with scheme injector-2

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Lattice design requirements for high-intensity proton linacs

- Zero current phase advance of transverse and longitudinal oscillations should be kept below 90º per focusing period to avoid parametric resonance.
- Transverse and longitudinal wavenumbers must change adiabatically.
- Avoid energy exchange between the transverse and longitudinal planes via space-charge resonances.
- Provide proper matching in the lattice transitions to avoid serious halo formation.

The RFQ

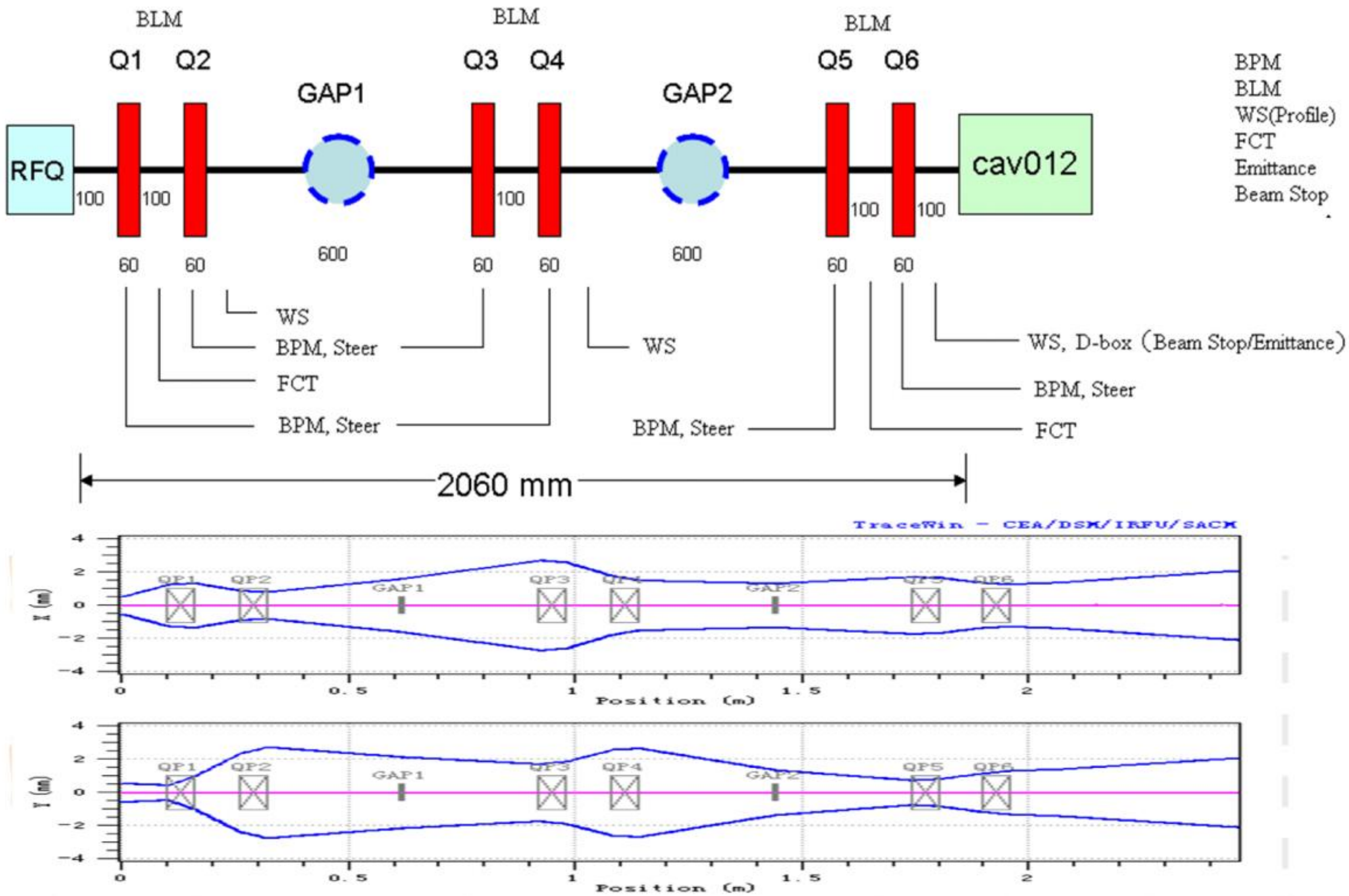
- RFQs are the only accelerating components in room- temperature
  - It is very difficult to develop a CW proton RFQ due to very large heat load density
  - Four-rod structure
  - Different choice on RF frequency: 162.5 or 325 MHz
- Design constraints from the previous RFQ experience at IHEP:
  - Section length: <1.2
  - Number of sections: <4

Parameters	Value
Frequency (MHz)	325
Injection energy (keV)	35
Output energy (MeV)	3.2128
Pulsed beam current (mA)	15
Beam duty factor	100%
Inter-vane voltage V (kV)	55
Beam transmission	98.7%
Average bore radius r_0 (mm)	2.775
Vane-tip curvature ρ_t (mm)	2.775
Maximum surface field (MV/m)	28.88 (1.62Kilp.)
Cavity power dissipation (kW)	272.94 [1.4* Psuperfish (194.96)]
Total power (kW)	320.94
Input norm. rms emittance(x,y,z) (πmm.mrad)	0.2/0.2/0
Output norm. rms emittance(x/y/z) (πmm.mrad/Mev-deg)	0.2/0.2/0.0612
Vane length (cm)	467.75
Accelerator length (cm)	469.95

Max Density:

(3.77 kW/cm^2)

MEBT1 layout



BPM	6
BLM	3
WS(Profile)	3
FCT	2
Emittance	1
Beam Stop	1

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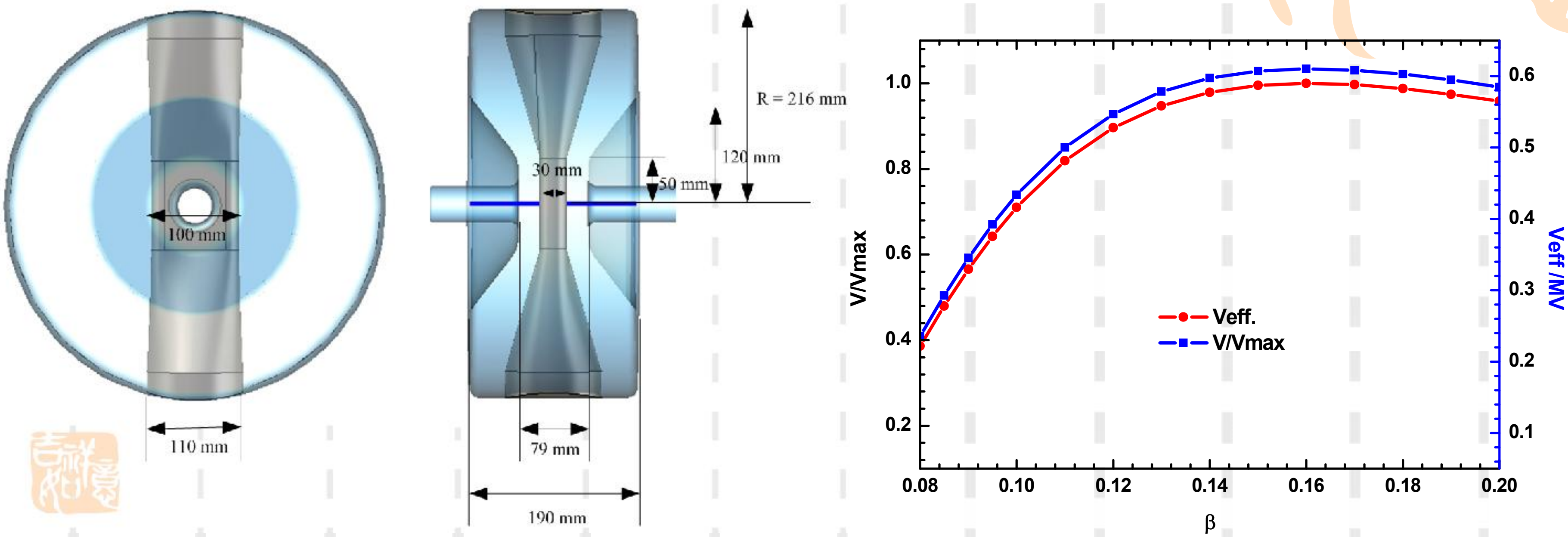
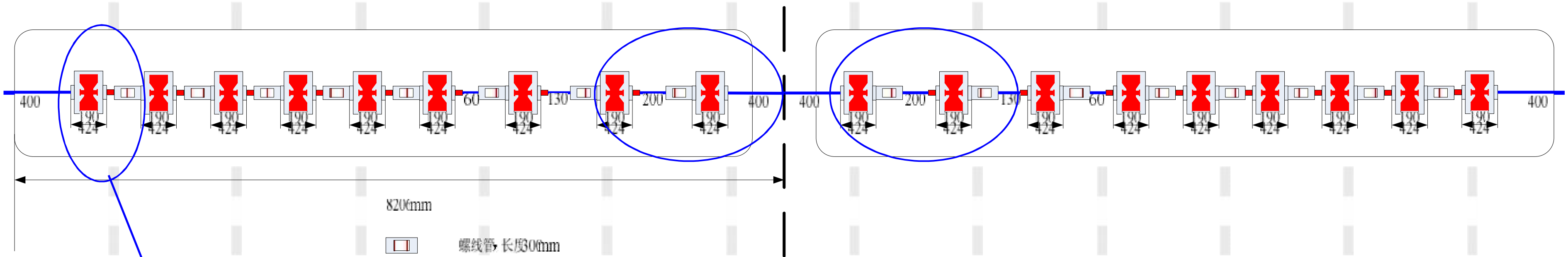
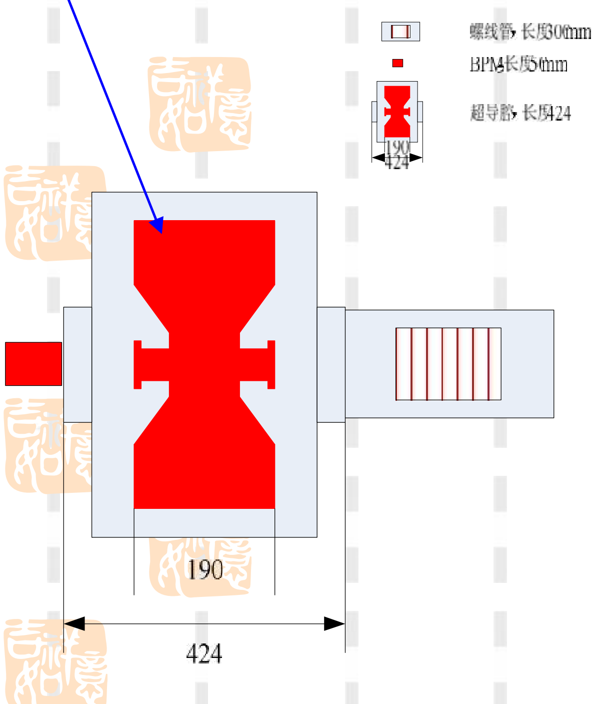
Spoke012 cavities



β_g	Freq. MHz	Uacc. Max MV	Emax MV/m	Bmax mT	R/Q
0.12	325	0.63	25	42	125

Lattice design of spoke012 section: Solution 1





Anti-symmetric lattice

18 cavities

16 solenoids

2 cryomodules with length of 8.2 m;

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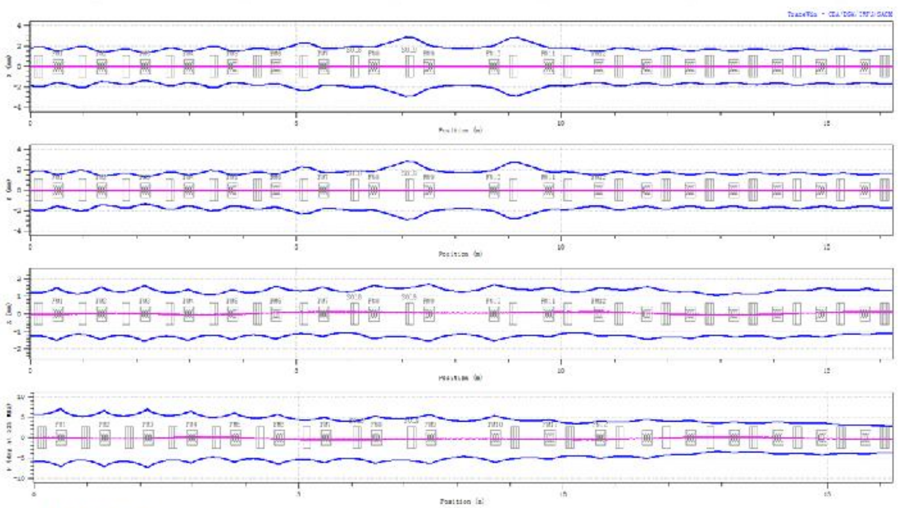
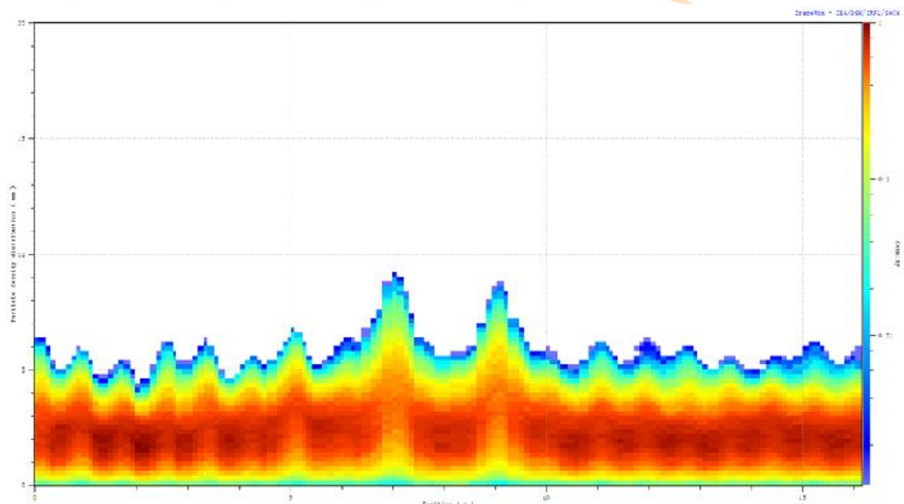
Dynamics study results

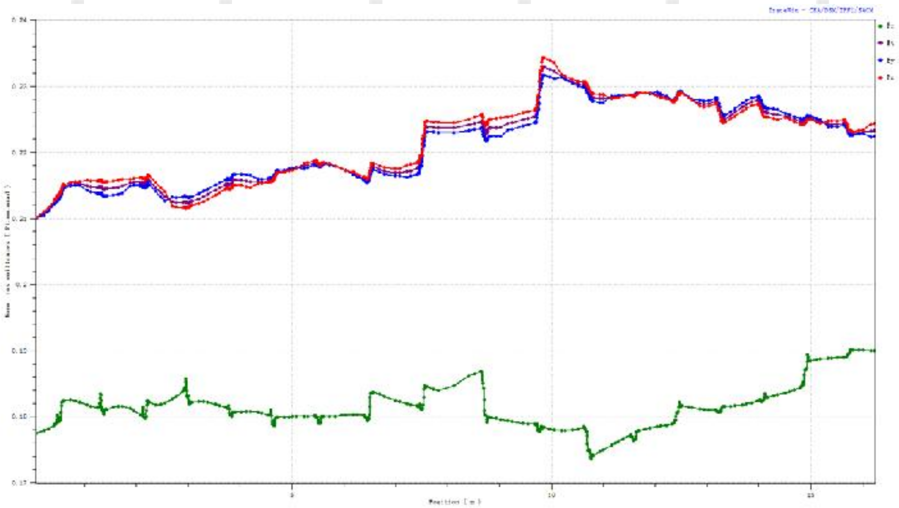


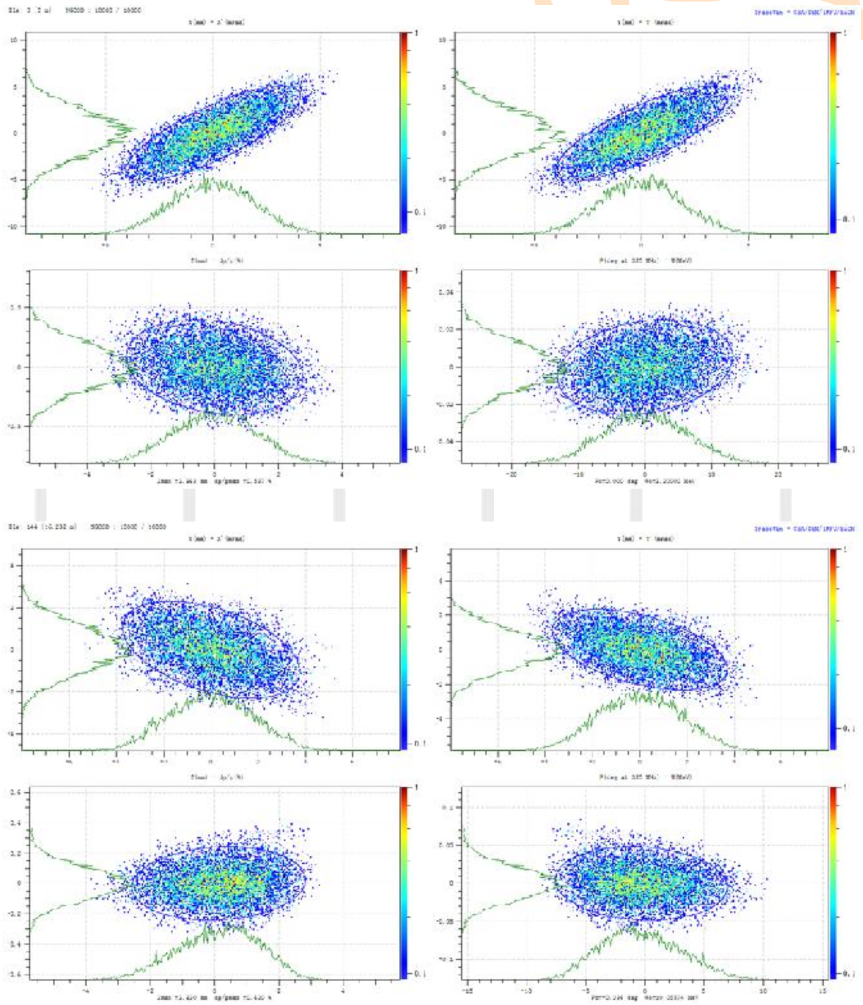


RMS envelope <3 mm

Maximum envelope < 10 mm

Emittance growth





Transverse emittance growth < 7%

Longitudinal growth: <10%

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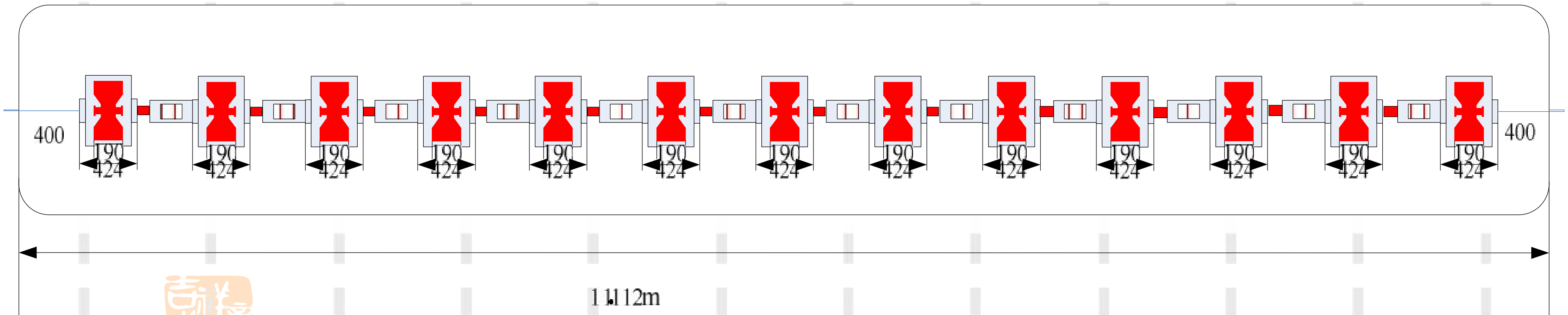
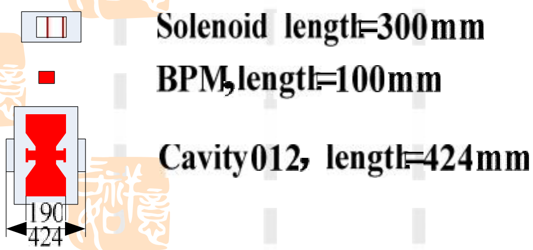
Solution 2: one crymodule with increased acceleration gradient



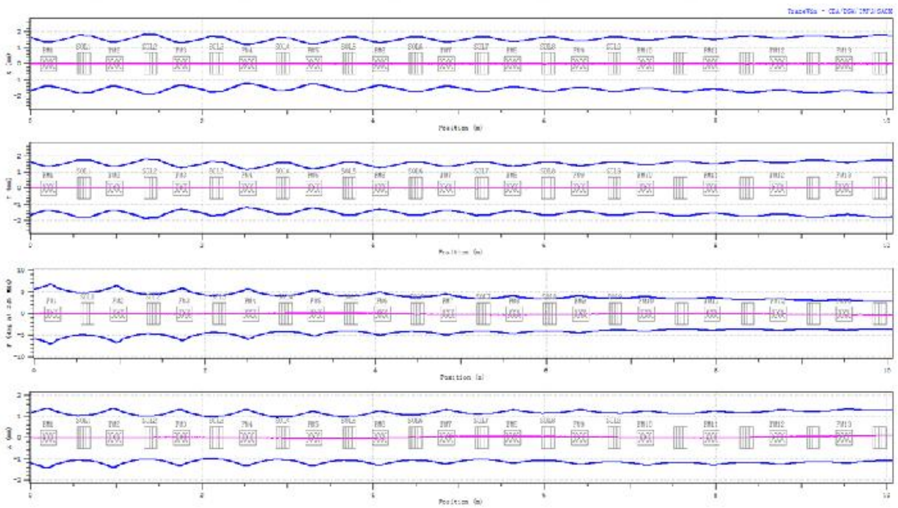


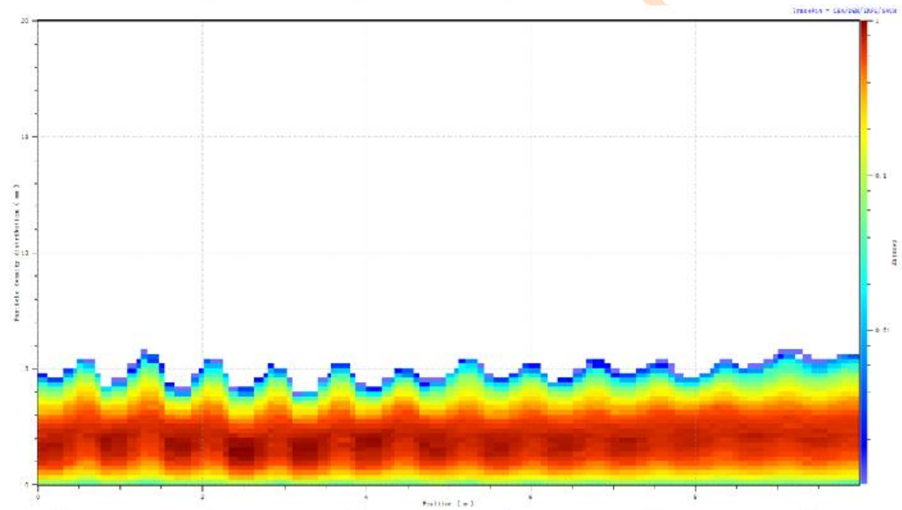
Total: 13 cavities, 12 solenoids

Maximum surface electric field is increased from 25 to 33 MV/m

Maximum surface magnetic field is still below mT

Dynamics study results





RMS envelope: < 2 mm

Maximum beam size: < 6 mm

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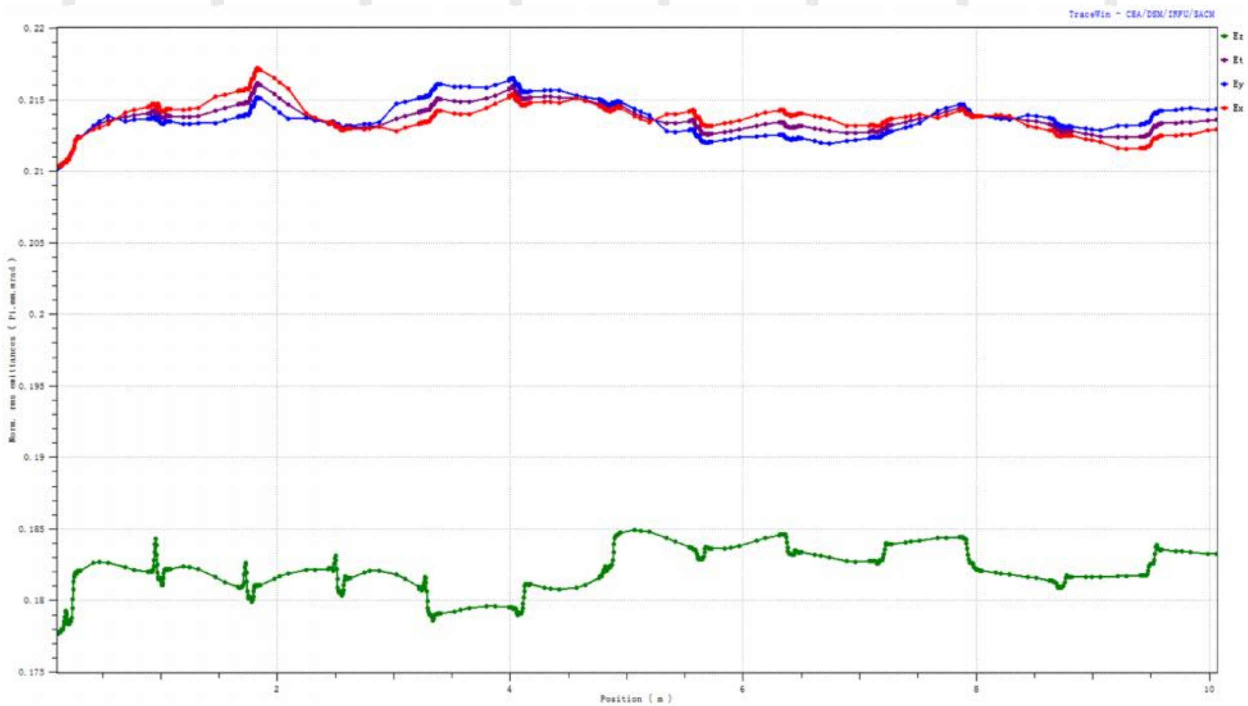
Emittance growth

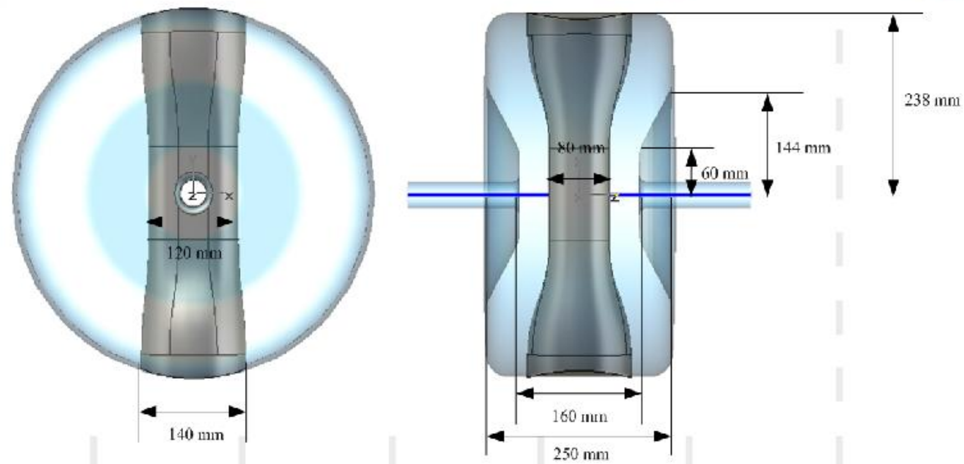


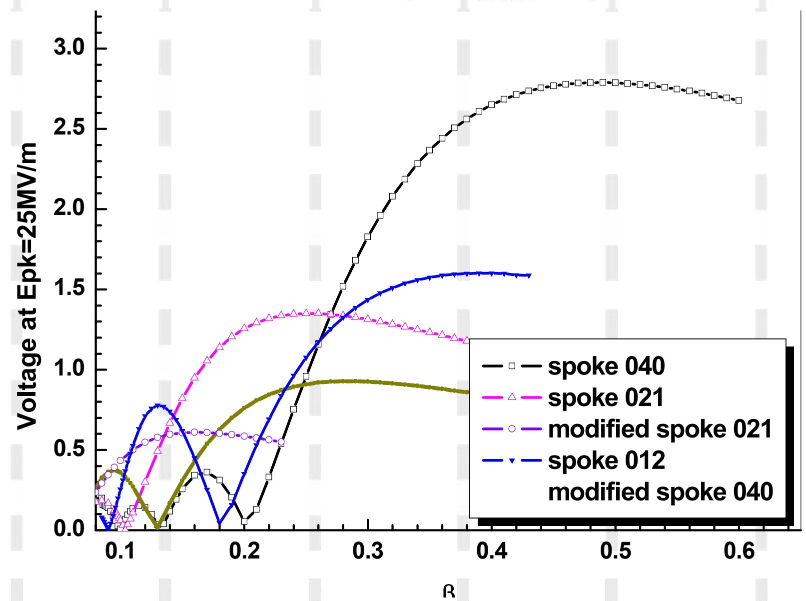
Transverse emittance growth: < 2%

Longitudinal emittance growth:< 4%

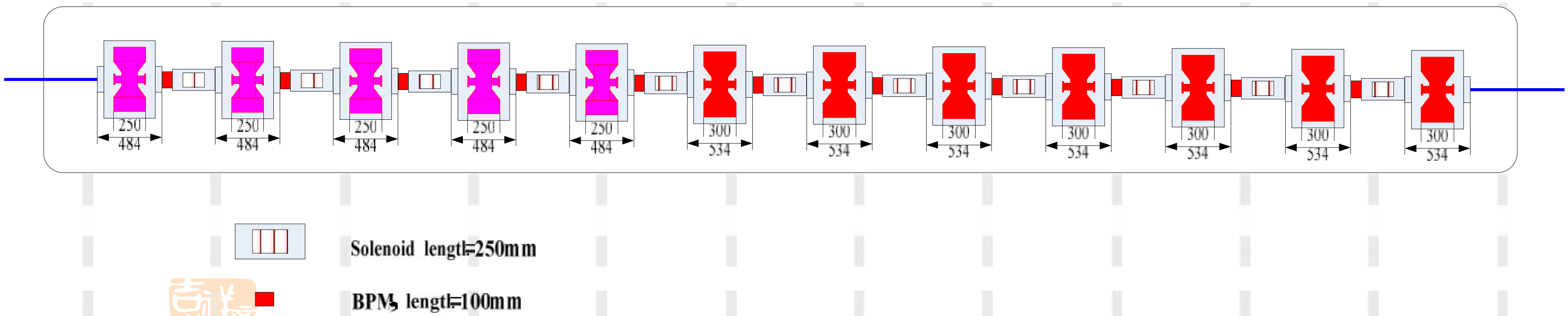
Solution 3: based on spoke cavities on 3βλ/2 mode

- Motivation
  - Poor performance of very low beta cavity
    - Mechanical stability
    - Frequency stability
- Method with 3βλ/2 mode
  - Increasing the gap width and stem thickness
- Gains
  - Rigidity, Frequency sensitivity, Voltage
- Demerit
  - Narrower β range (one more type cavity)





Lattice based on $3\beta\lambda/2$ cavities



- Total number of cavities: 12
  - M_spoke026: 5
  - M_spoke036: 7
- Maximum surface field: 32.5 MV/m
- CM length: 10.8 m;

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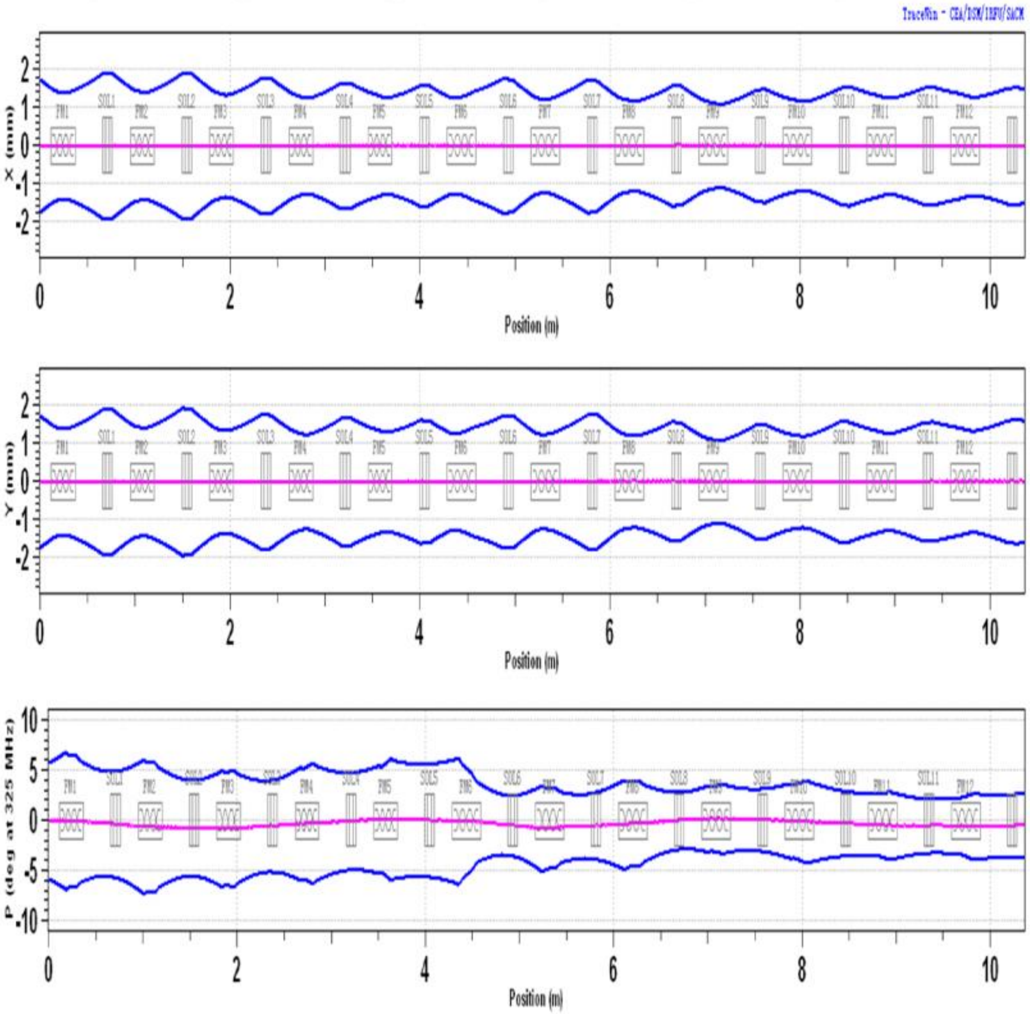
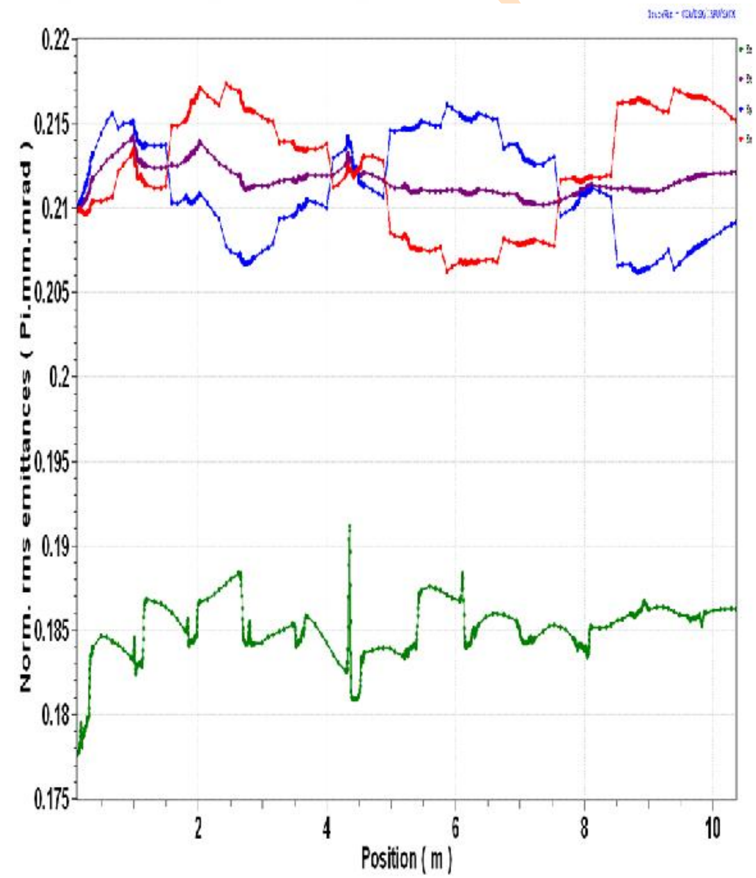
Dynamics study results



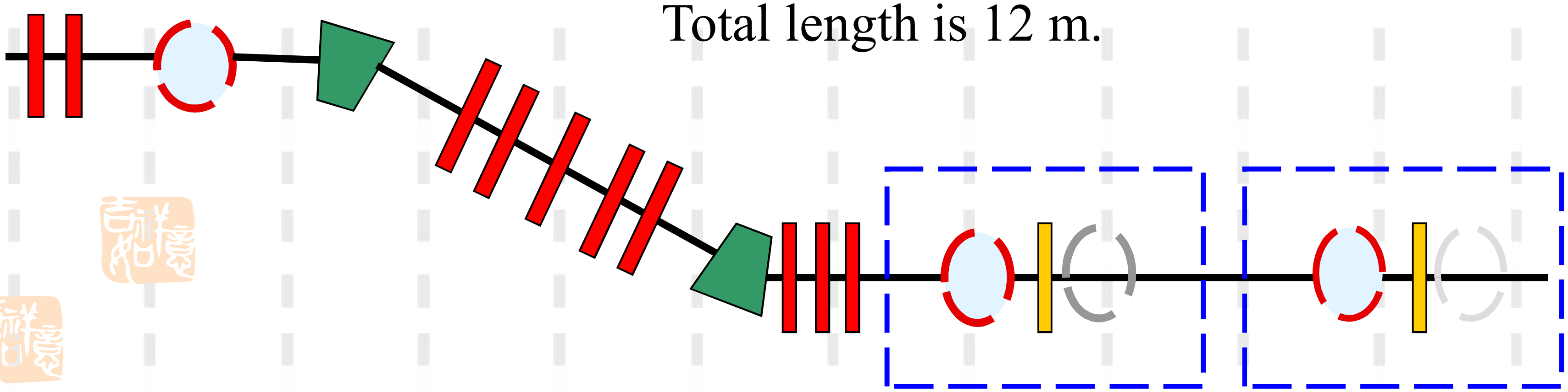


MEBT2

One branch (of two):

10 Quad +5 Buncher + 2 solenoid+2 Bend

Total length is 12 m.



- No buncher in dispersive section
- 5 Quad+ 2 bend for achromatism and keep beam envelope smooth
- 3 bunchers for longitudinal matching (2 are standard Spoke021 cells)
- Translational distance 45cm for magnet installation

List of superconducting cavities in main linac

Cavity type	β_g	Freq. MHz	Uacc. Max MV	Emax MV/m	Bmax mT
single spoke	0.21	325	1.32	25/32.5	44.8/58.2
Single spoke	0.40	325	2.79	25/32.5	64.8/84.2
5-cell elliptical	0.63	650	7.68	35/45.5	48.3/62.8
5-cell elliptical	0.82	650	15.47	35/45.5	70.4/91.5

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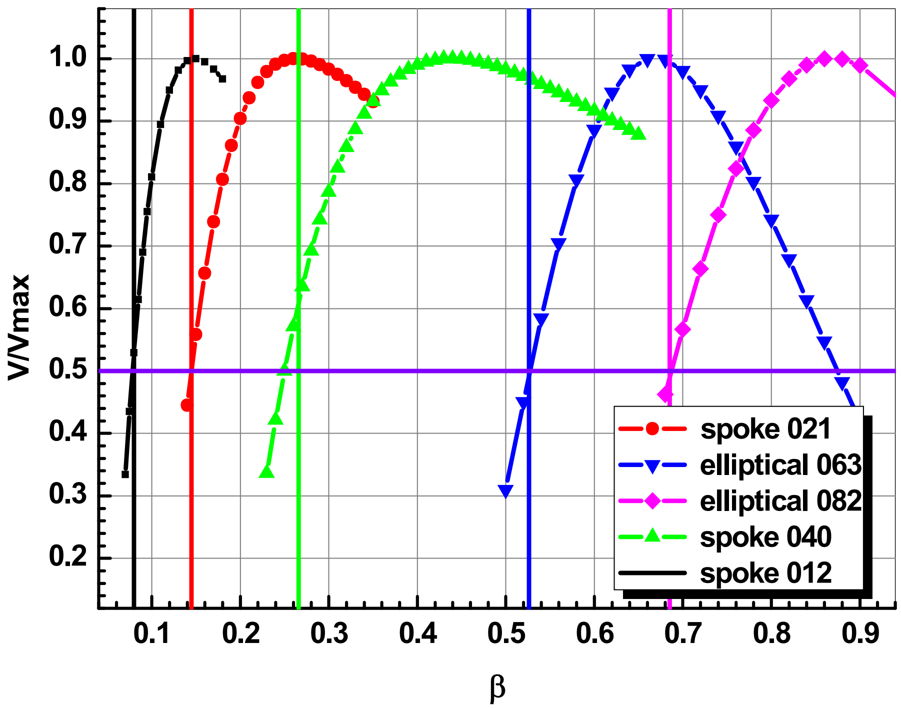
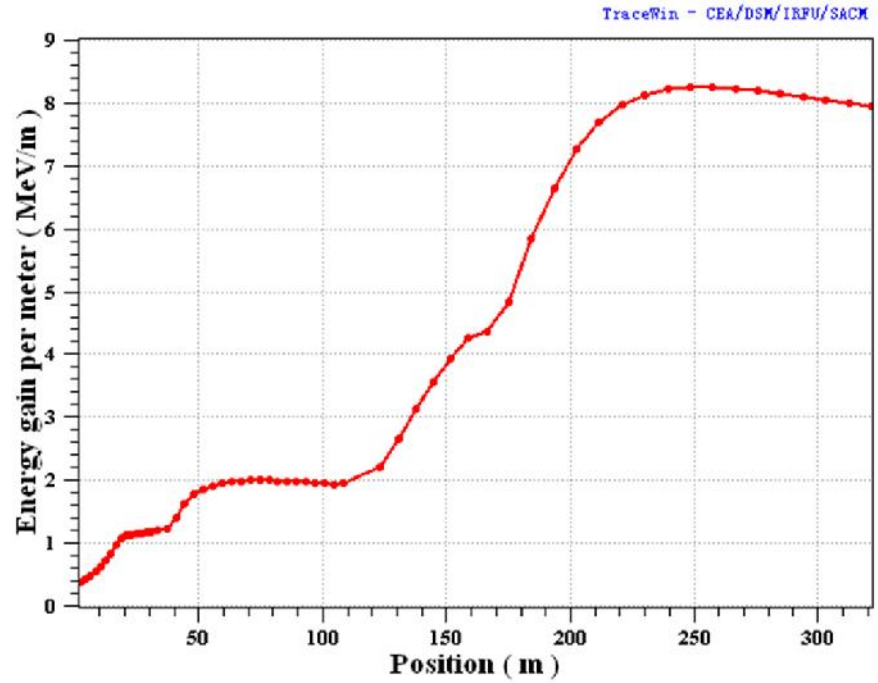
Acceleration efficiency

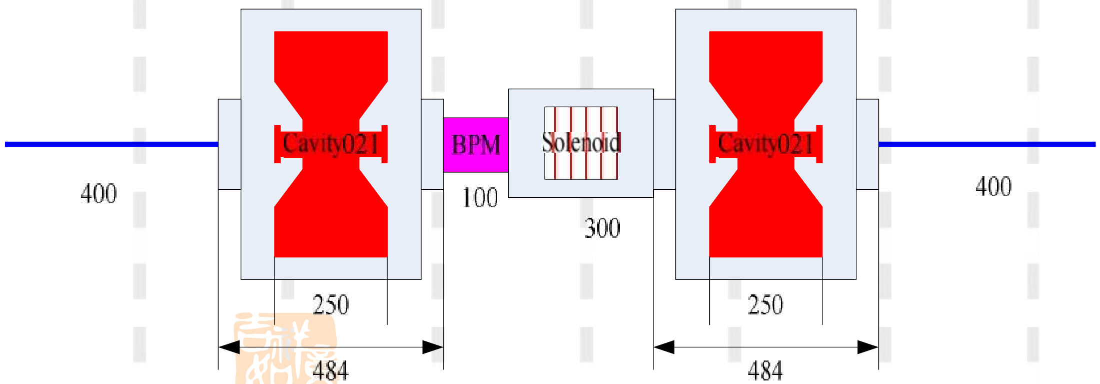




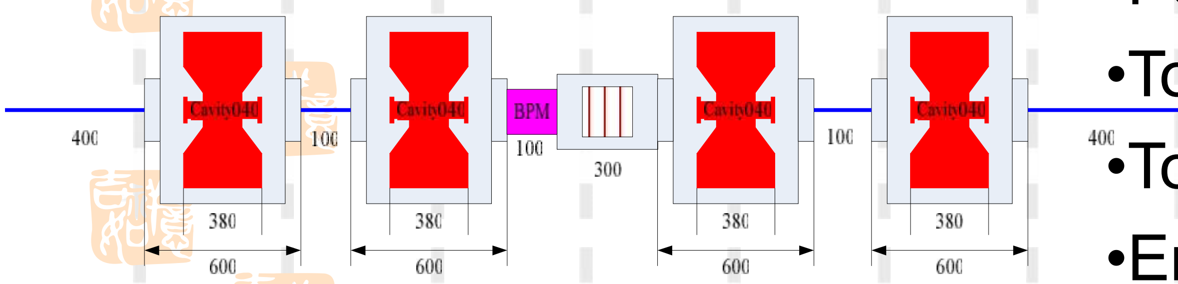
1、Efficiency for each cavity is greater than 0.5;

2、Acceleration gradient changes smoothly at the transition between different sections;

Lattice design: Spoke021 and Spoke040



- Period length: 2.168 m
- Total periods: 14
- Total cavities: 28
- Energy range: 10~34 MeV



- Period length: 3.8 m
- Total periods: 18
- Total cavities: 72
- Energy range: 34~178 MeV

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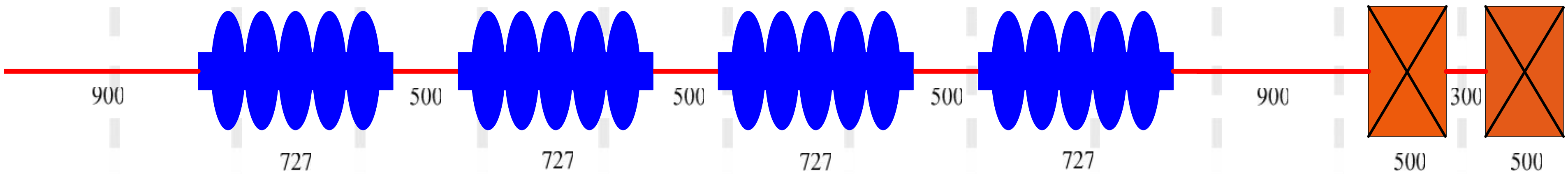
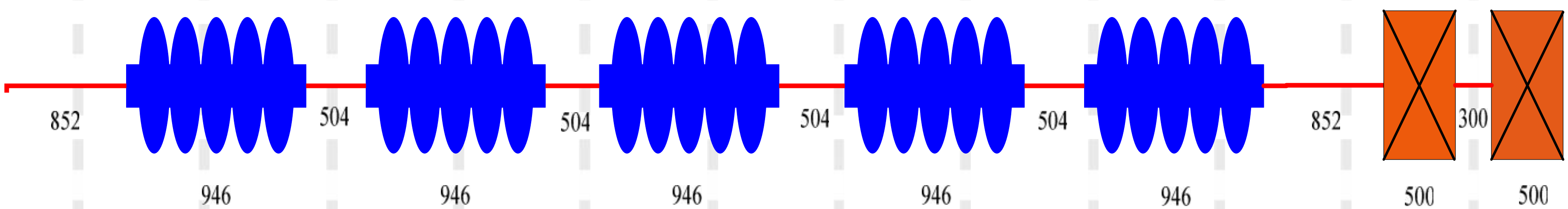
Lattice design: Ellip063



- Period length: 7.508 m
- Total periods: 7
- Total cavities: 28
- Energy range: 178~367 MeV

Lattice design: Ellip082



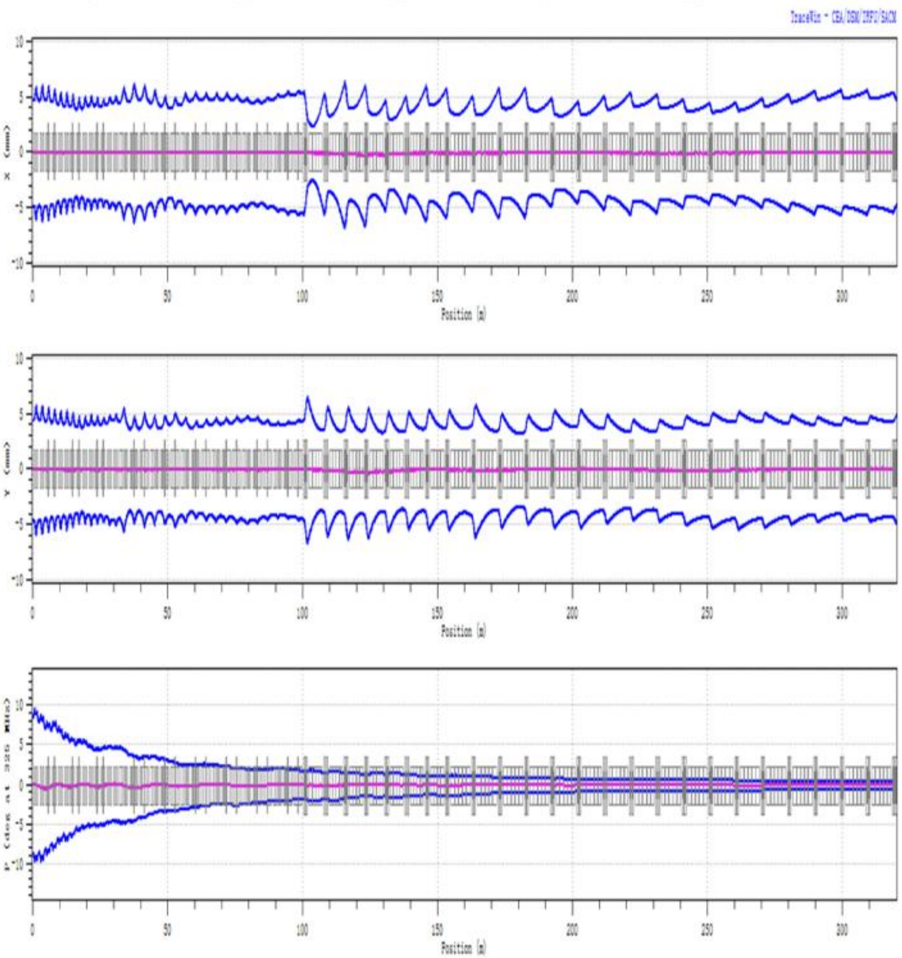
•Period length: 9.75 m

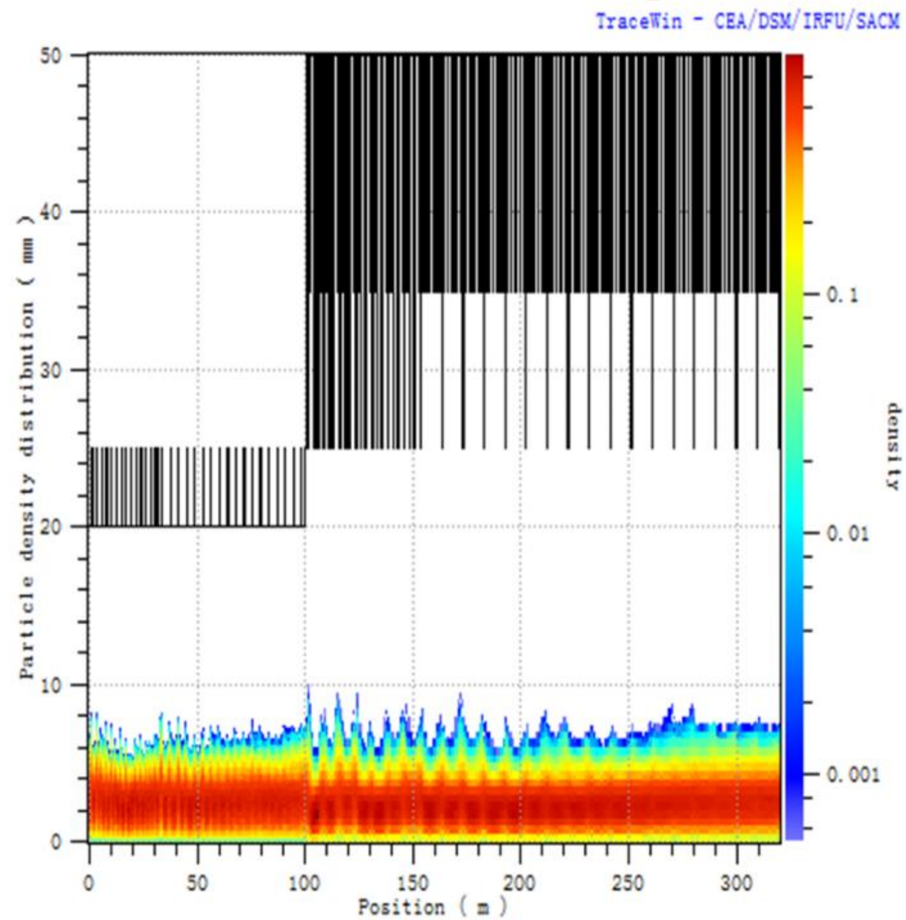
•Total periods: 17

•Total cavities: 85

•Energy range: 367~1500 MeV

Dynamics study results





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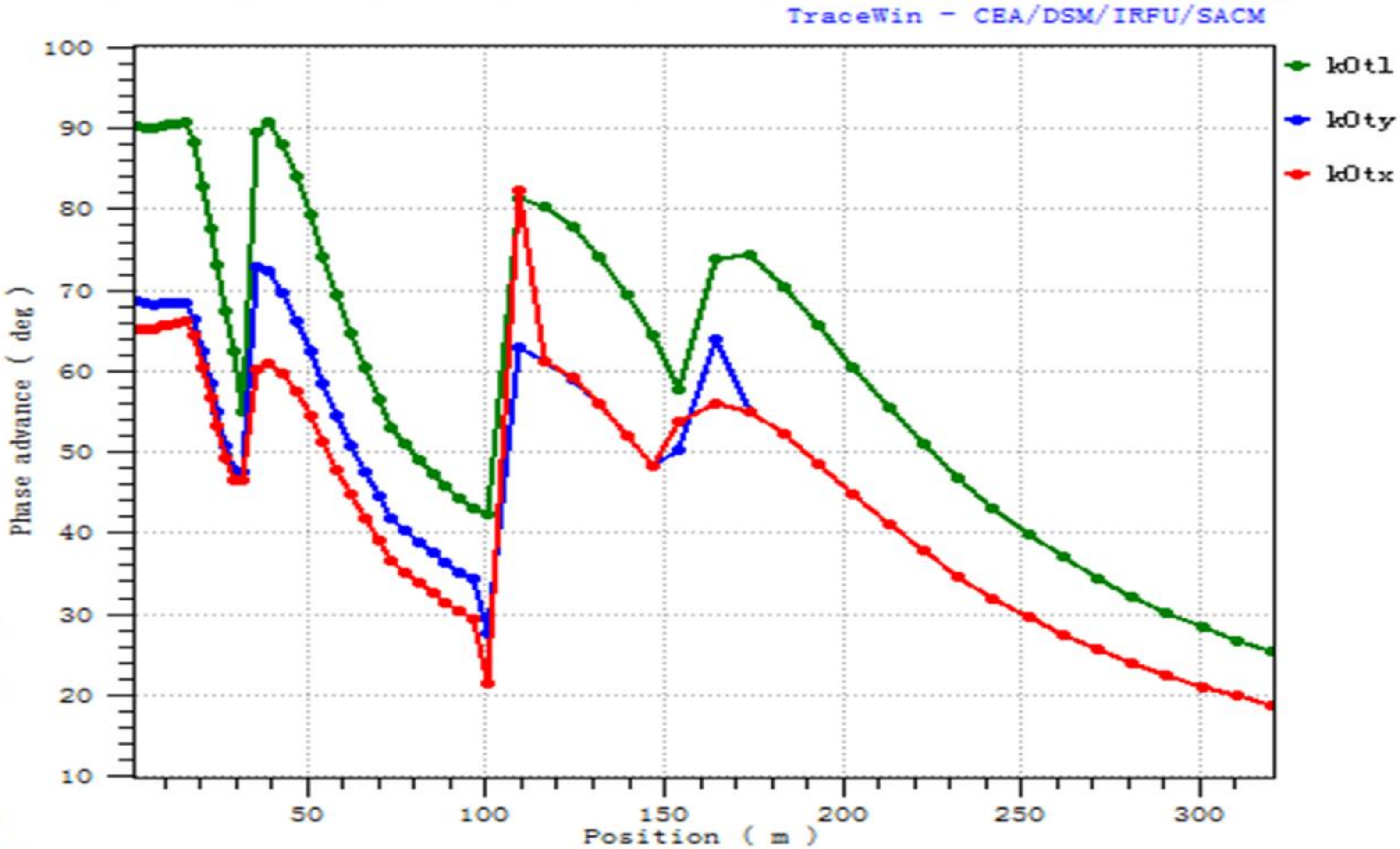
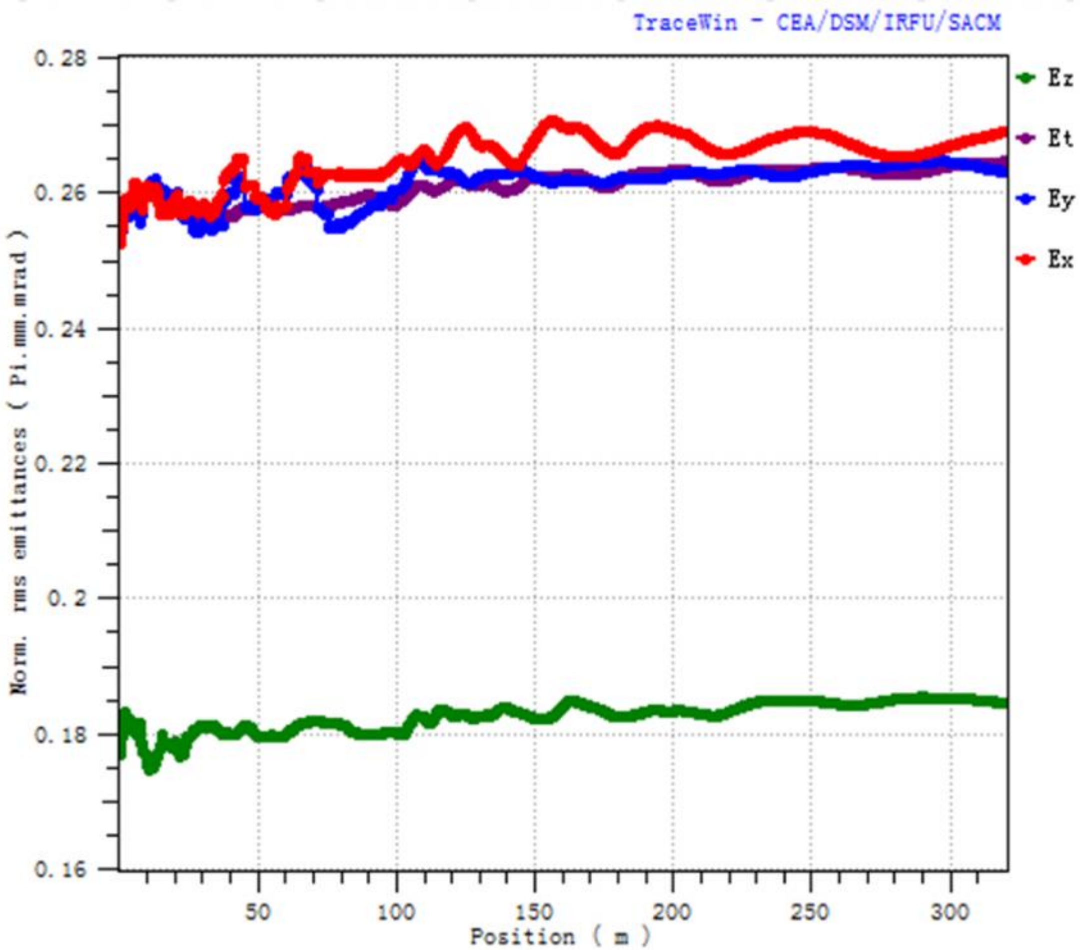
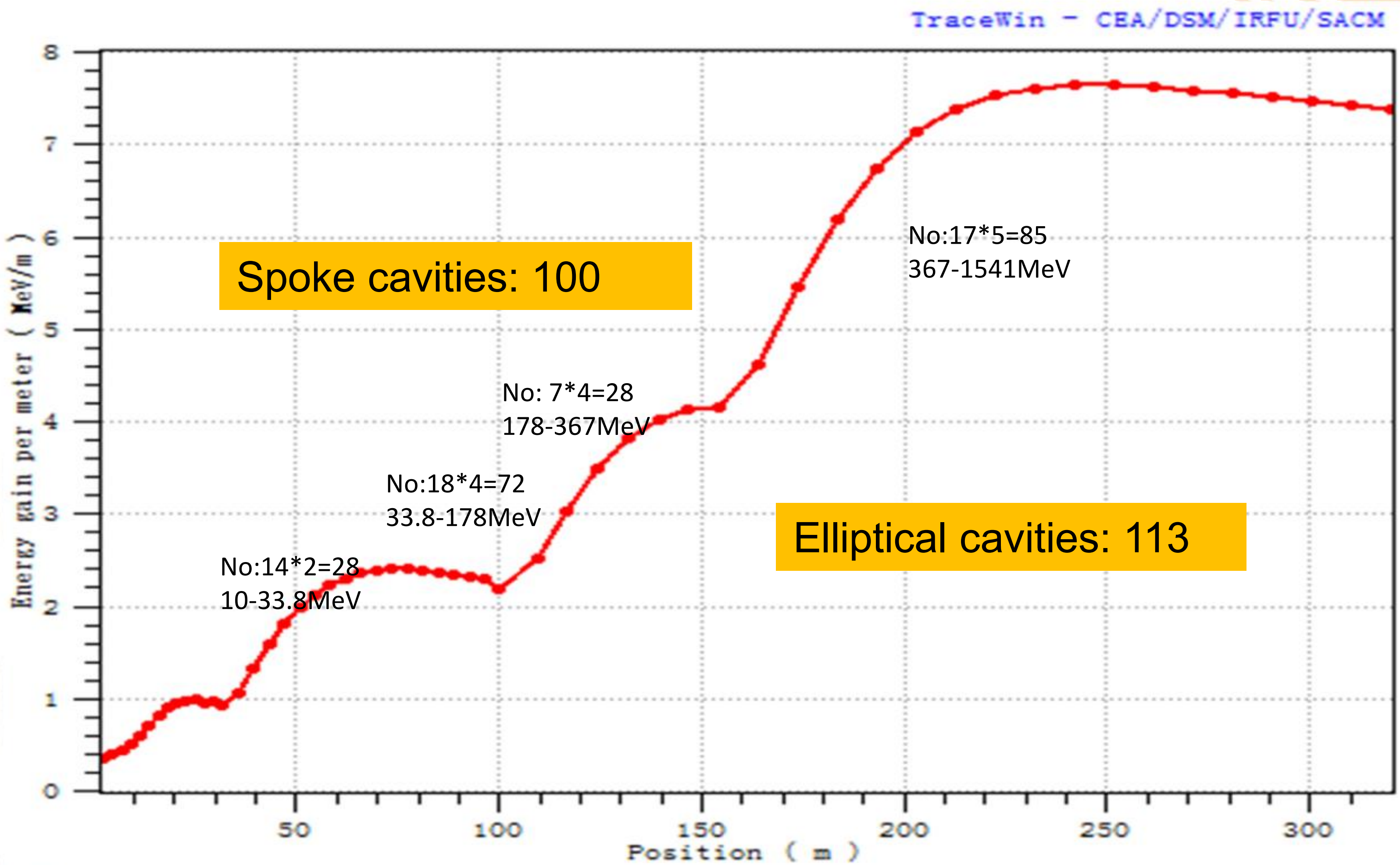
Zero-current phase advance



Emittance evolution



Energy gain


TraceWin - CEA/DSM/IRFU/SACM
Energy gain per meter (MeV/m)
Position (m)
Spoke cavities: 100
Elliptical cavities: 113
No:14*2=28
10-33.8MeV
No:18*4=72
33.8-178MeV
No: 7*4=28
178-367MeV
No:17*5=85
367-1541MeV

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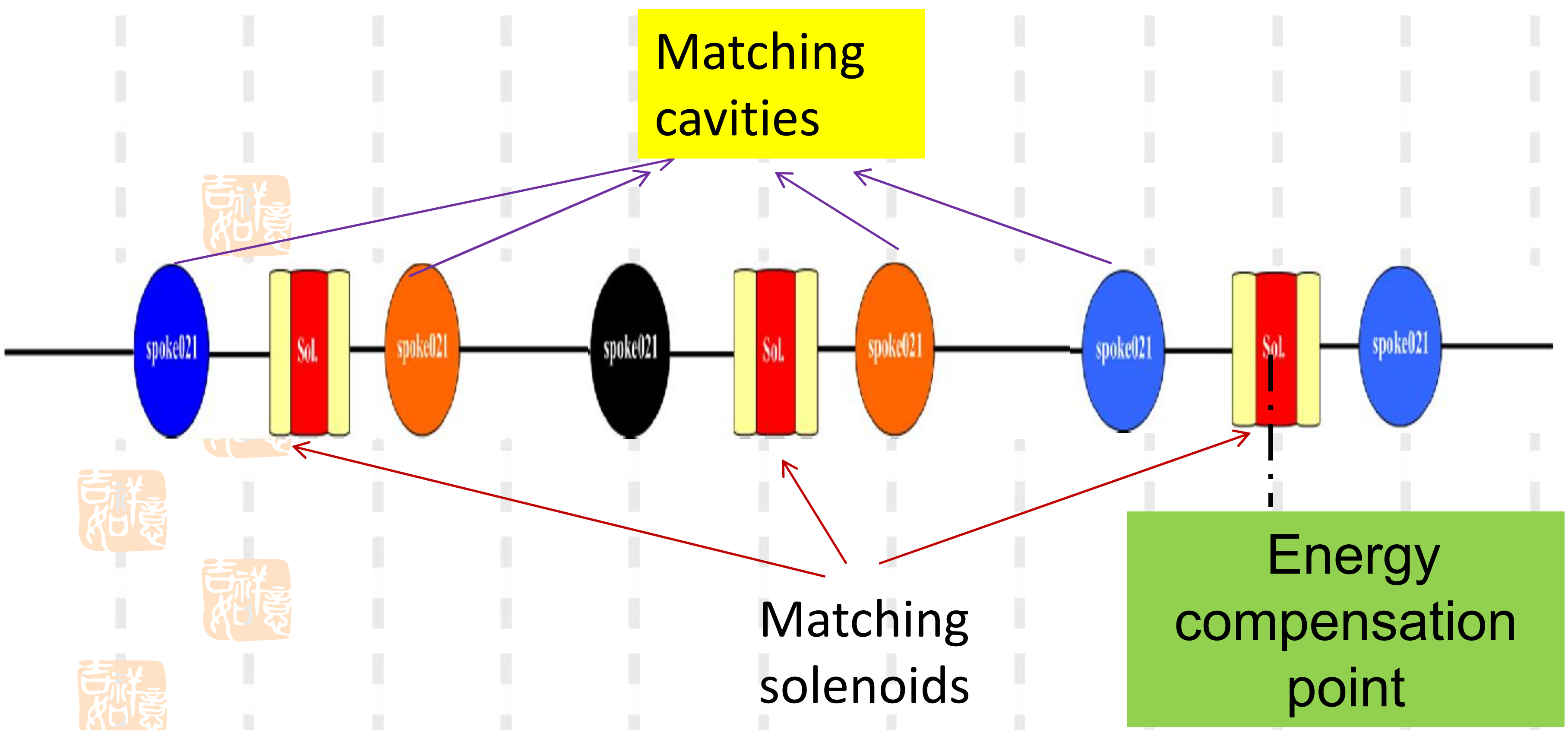
Local compensation of failures

- Preliminary studies on local compensation of cavity and solenoid failures have been carried out for Spoke021 section and Spoke040 section.
- One cavity failure in a cell can be well compensated by adjusting neighboring cavities. (rms emittance growth less than 10%)
- One solenoid failure is difficult to be compensated, especially at the beginning of the Spoke021 section

Failure compensation at Spoke021 section



Key technology R&D for C-ADS linac

- Strategy
  - *Parallel developments of different scheme or technical solutions for the injector (IHEP and IMP)*
  - *Development by steps (Phase 0, I, II, III)*
- Some key technology R&D
  - *Ion Source: stable operation*
  - *CW RFQ: cooling problem*
  - *SC Spoke cavities: development, unproven performance*
  - *SC CH cavities: very challenging (candidate for IMP injector)*
  - *High power couplers: especially for CW RFQ*
  - *Cryomodule: long cryomodule with many cavities and solenoids*
  - *RF power source (CW Klystron, CW SSA, LLRF)*
  - *Control & Instrumentation*
  - *…*

R&D studies (Phase 0)

- The budget has been approved (1.8 BCHY or 280 M$ in total)
  - Accelerator: 640 MCHY (425 M for IHEP and 215 M for IMP)
- 2011-2013
  - Physics design and technical designs
  - Developing CW RFQ, SC cavity prototypes (spoke, HWR and CH) for the injectors
  - CW test of first 5 MeV of two injectors
  - Infrastructure or laboratory building-up
- 2014-2016
  - Two different injectors testing with CW, 10-MeV and 10-mA
  - Construction of main linac section (10-50 MeV)
  - CW test of the 50-MeV linac

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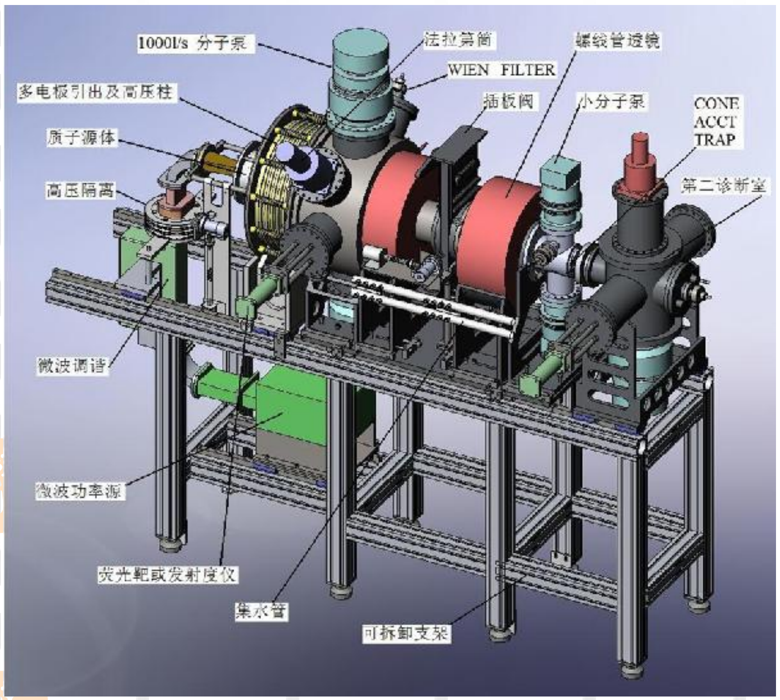
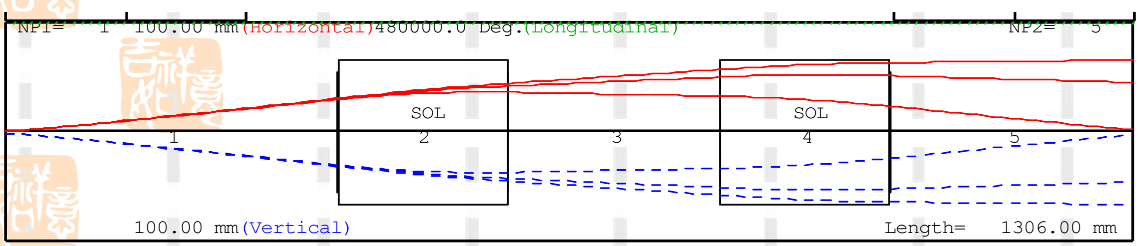
Some R&D work already carried out

Ion Source: ECR & LEBT (IMP)





H^+、H_2^+ & H_3^+
Beam profile

High-duty factor RFQ (IHEP)

- A 3.5 MeV - 40 mA RFQ of 7-15% duty factor (supported by “973” program) was constructed and commissioned at IHEP, one of the most powerful RFQs under operation condition.

	973 RFQ	ADS RFQ
Frequency	*352MHz*	*325MHz*
Energy	*3.5MeV*	*3MeV*
Duty Factor	*~15%*	*CW*
Operating	*Short time*	*Long time*

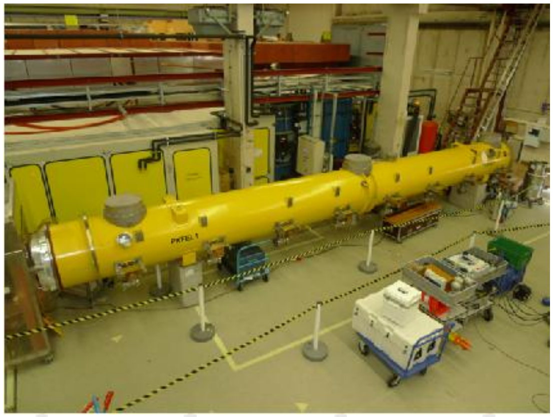
High power input couplers (IHEP)

(Supported by the BEPC SC cavity development program)

≥400kW

Cryomodules (IHEP)

Cryomodule for BEPCII 500MHz SC Cavity



Cryomodule named PXFEL1 was passed the cryogenic test at DESY in July. 2009.

Control & Instrumentation (IHEP)

- Controls:
  - Digitalized control system has been developed for the CSNS project, and can be used in the C-ADS
  - EPICS, XAL etc. developed with the CSNS project (BEPCII)
- Instrumentation
  - Many beam diagnostic devices have been developed or are under development under the “973” program and the CSNS project. They can be used in the C-ADS, such as BLM (including ion chamber, FBLM), BPM, BCT, Wire Scanner, double-slit emittance measurement system.

Summary

I. Sustainable nuclear energy has high priority in China.

II. The C-ADS program has been officially started under the coordination of CAS, and is led by three CAS institutes.

III. The R&D phase for the driver linac is to build a SC linac with a CW beam of 50-MeV and 10-mA, and relevant infrastructure.

IV. It is a great challenge to build a high-performance CW proton linac. Strong collaboration with international leading laboratories is very important. This is not only an important step towards the ADS but also a contribution to the accelerator community.

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Thanks for your attention！